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# Proton Charge Radius and Precision Tests of QED

JAN C. BERNAUER

*Laboratory for Nuclear Science  
Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, MA  
02139*

The “proton radius puzzle” remains unsolved since it was established in 2010. This paper summarizes the current state and gives an overview over upcoming experiments.

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# 1 The proton radius puzzle

The properties of the proton, one of the basic building blocks of the matter around us, have been a research target for a long time. Recently, a series of precise experiments of the protons charge radius have produced results which are in strong disagreement, casting doubt on our knowledge of one of the protons fundamental properties and our understanding of the underlying physics. The discrepancy falls between the different methods for measuring the protons radius. The following sections address the three principal methods employed to date.

## 1.1 Elastic electron-proton scattering

The cross section for scattering an electron beam off a proton target in the first Born approximation is given by

$$\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \frac{1}{\epsilon(1+\tau)} \left[ \epsilon Q_E^2(Q^2) + \tau G_M^2(Q^2) \right], \quad (1)$$

with the negative four-momentum-transfer  $Q^2$ , the kinematical variables  $\tau = Q^2/4m_p^2$ ,  $\epsilon = 1/(1 + 2(1 + \tau) \tan^2 \frac{\theta}{2})$ , the Mott cross section  $(d\sigma/d\Omega)_{\text{Mott}}$  and the electric and magnetic form factors  $G_E, G_M$ . Exploiting the cross section's dependency on the kinematical variables, one can disentangle both form factors from a series of cross section measurements, for example via the Rosenbluth separation method. This gives access to the form factors over a large range of four-momentum transfers.

The root-mean-square charge radius,  $r_e$ , is defined in terms of the slope of the electric form factor  $G_E$  at  $Q^2 = 0$ ,

$$r_e = 6\hbar^2 \left. \frac{dG_E}{dQ^2} \right|_{Q^2=0}. \quad (2)$$

Extractions of this type typically achieve uncertainties on the order of 1%.

## 1.2 Hydrogen spectroscopy

The finite size of the proton shifts the atomic energy levels of hydrogen by small amounts. This effect can be measured in the lower S-states. Historically, the proton radius has been a correction to level calculations in high precision QED tests. Experiments have progressed to a state where the uncertainty in the radius is now one of the limiting factors. Turning the argument around and assuming the correctness of QED, these kind of experiments can be used to extract a proton radius.

One way is to measure the 2S-2P transition, which gives the Lamb shift, and with that the proton radius. In a different approach, the transition 1S-2S and a second

transition from 2S to a higher state like 8S or 8D are measured. The proton radius is then extracted using simultaneous fit of the radius and the Rydberg constant.

Currently published measurements are typically less precise than the results from scattering experiments. Combining the available data, however, leads to an extraction with similar uncertainties.

### 1.3 Muonic Hydrogen spectroscopy

In recent years, it became possible to study muonic hydrogen, the bound state of a proton and a muon, with spectroscopy. The muon, because of its larger mass, has a 200 times smaller orbit and with that an about  $200^3$  higher probability of being inside the proton. Consequently, the finite size effect is substantially larger, making a more precise extraction of the radius possible. The published results quote more than ten times smaller uncertainties.

### 1.4 The puzzle

Figure 1 shows the result of recent determinations. For scattering, the results from [1,2] and [3] are presented. The former is the result of a measurement of more than 1400 cross sections, about twice of all other existing proton form factor data. The latter is an extraction using almost all available data except the Mainz data set. It is therefore independent. The H-spectroscopy result is taken from the global fit of CODATA 2010 [4]. These measurements are all in agreement with each other; a combined result of the electron measurements is shown as “electron avg”. In contrast to this, the two published results from muon spectroscopy [5,6], are consistent with each other, but more than 7 standard deviations away from the electron result.

The discrepancy, dubbed the “proton radius puzzle”, has driven a wide range of theoretical and experimental efforts, and has even found its way into popular science literature [7]. Since the publication of [1] and [6] in 2010, it has withstood all attempts at a solution.

## 2 Possible solutions

The puzzle has prompted a lot of research, leading to a large number of papers trying to solve the discrepancy. However, many have been ruled out by further studies. None has seen widespread acceptance by the community so far. In this section, some of the proposed solutions will be discussed. Due to the sheer number, this paper can only highlight some of the ideas. Instead, I will try to give a categorization and a personal perspective.

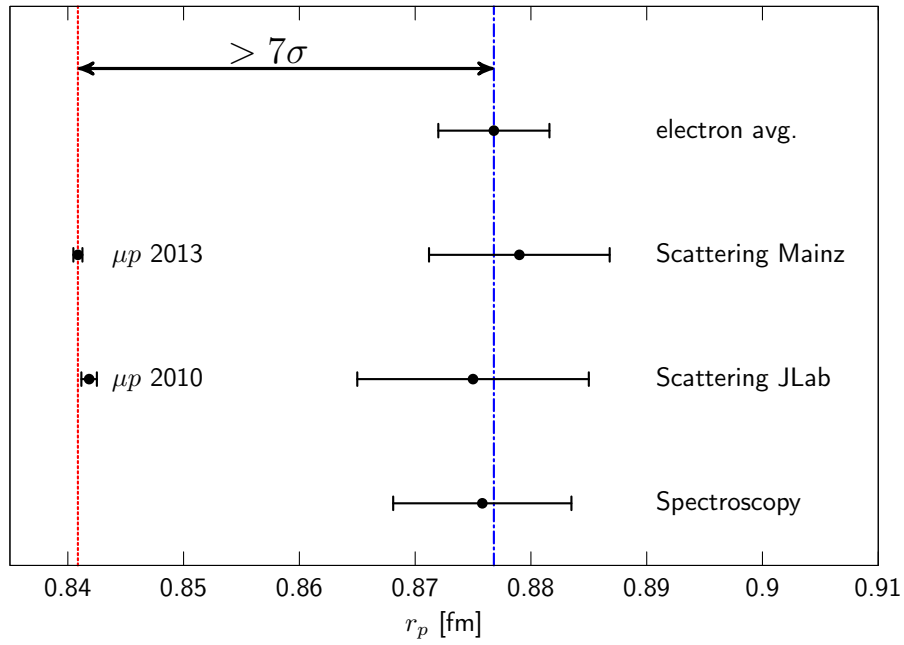


Figure 1: Selected results for the proton radius. The extractions from electronic measurements from Mainz [1,2] and Jefferson Lab [3] are in agreement with spectroscopy results [4], but in strong disagreement with the muonic results [5,6].

## 2.1 Errors in experiment execution

Errors in execution of either the muon experiment, or both atomic hydrogen spectroscopy and scattering could explain the difference. On the muon spectroscopy side, the measured resonance is shifted from the range expected by the electronic results by far more than its width, and the results from both measured lines are very consistent. Only a few concerns about possible problems have been raised, all of which have been studied and ruled out by the CREMA collaboration.

On the other hand, conspiring mistakes in the electron-based extractions seem unlikely, just by the number of experiments which are all in agreement. However, it is worthwhile to note that the bulk of spectroscopy results are produced by the same group and a systematic error might affect all results at once.

The different data sets produced in scattering experiments by different groups with different setups span decades in time. It is remarkable how well they are in agreement [2]. Specific concerns regarding the Mainz experiment have been subsequently ruled out by the Mainz collaboration.

## 2.2 Errors in experiment analysis

For the electron experiments, errors in analysis procedures are a greater concern, since they may affect multiple experiments in the same way. For scattering experiments, the extrapolation of the data to  $Q^2 = 0$  is crucial. While the possibility of structure below the Mainz data set seems unlikely—structure there would mean that there is a surprising large amount of the charge at very large radii—it may be possible to find form factor models which do not exhibit this problem, produce a small radius and still fit the experimental data well. Many fits of different parts of the world data set by different groups with different models have been performed. On the one hand, most of them reproduce the large radii, with a tendency to be even larger (*e.g.* [8–12]). On the other hand, the fits in [13–16] produce a radius compatible with the muon result, although with a substantially larger  $\chi^2/d.o.f.$ .

The scattering experiments have a rather small dependence on theoretical corrections, which are mostly well understood. However, several papers (*e.g.* [17–19]) investigated the effect of different treatments of two-photon-exchange, *i.e.* higher Born terms. They tend to reduce the radius, but can not explain the full discrepancy.

The spectroscopy results rely on theory to a much larger extent. In the wake of the puzzle, all components have been rechecked and improved, without finding relevant changes. One remaining uncertainty stems from the proton polarizability (see [20] and its citations), however, the general consensus seems to be that the effect is too small to explain the discrepancy.

## 2.3 New physics

The theory calculations rely on the assumption that our current understanding of the underlying physics is correct. If the puzzle survives any attempts to solve it within the standard theoretical framework, the solution might present itself in the most welcome outcome: new physics. Several such solutions have been proposed, and they can roughly be divided into two groups.

The first group introduces new concepts which invalidate some of the assumptions, but without any or with little modification to the Standard Model. This includes papers like [21], in which Walcher criticizes the approach in the theoretical calculations, and [22], in which Jentschura proposes the existence of light sea fermions.

The second group introduces bigger changes to the Standard Model. Particular interesting is the introduction of light dark matter (see, *e.g.*, [23–28]) since it might simultaneously solve the muon  $g-2$  anomaly. However, it seems that simple models for such dark matter can not reconcile both, and in fact, need a lot of fine-tuning to avoid being ruled out by other experiments. Li, Chen, Wang and Ni [29, 30] propose large extra dimensions to solve the puzzle.

## 3 Upcoming experiments

To study the puzzle further, a multitude of experiments are under way or planned. Indeed it is the expressed opinion of the majority of the community that such new data are needed to make any headway towards a solution.

### 3.1 Spectroscopy

On the muonic side, the CREMA collaboration has switched gears and is studying the spectra of heavier nuclei, with experiments on deuterium,  $^3\text{He}$  and  $^4\text{He}$  currently under analysis. Preliminary results from muonic deuterium indicate that the isotope shift, the difference between the proton and deuterium radius, is in good agreement with the value determined from electronic systems. The group also indicated that for helium, the radii are not different from the electronic values, however there is still a large theoretical uncertainty.

Several groups at LKB, MPQ, NPL and York University are trying to improve on the existing electronic hydrogen measurements using a variety of techniques.

Furthermore, groups at MPQ and VU University Amsterdam are preparing experiments on helium ions, while NIST is focusing on highly charged ions.

### 3.2 Scattering experiments

The A1 collaboration in Mainz, the same group that performed the high precision proton form factor measurement, is pursuing several experiments regarding the radius. With an approach similar to the proton form factor measurement, data were taken on electron-deuterium scattering in 2012. The analysis is ongoing. It is planned to extend the proton measurement to higher four-momenta using the higher beam energies of MAMI-C.

As described earlier, the extrapolation to  $Q^2 = 0$  is critical. Using initial state radiation to lower the effective beam energy, Mainz aims to lower the current limit for  $Q_{\min}^2$  by more than an order of magnitude [31]. The approach has significantly different systematics than the classical approach. A confirmation of the radius will therefore rule out several possible sources of error. Data were taken in 2013, and the data analysis is ongoing.

With a similar aim, but different methodology, is the PRad experiment [32] at Jefferson Lab. Using a high resolution, large acceptance hybrid calorimeter and a windowless target, elastic scattering at extremely forward angles will be studied. The concurrent measurement of Møller scattering will enable good control of the absolute normalization.

A missing piece in the puzzle will be filled by the MUSE collaboration: While we have results from both scattering and spectroscopy on the electronic side, we miss precise scattering data of muons off of protons. The MUon Scattering Experiment [33] aims to measure both  $e^{+/-}$  and  $\mu^{+/-}$  cross sections using the powerful low-energy beam of the Paul Scherrer Institute. The measurement of the charge symmetry will allow the group to control two-photon exchange corrections, while the measurement of both species with the same detector will enable a direct comparison of the cross sections and radii, with small systematic uncertainties.

## 4 Conclusion

In the four years after its discovery, the proton radius puzzle has not been solved. If anything, it has grown stronger. In the next five years, a large number of experiments will shed some more light on this intriguing problem.

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